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Numerical Investigation of Multi-Plume Rocket Phenomenology

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Abstract

The Generalized Implicit Flow Solver (GIFS) computer program has been modified and used for three-dimensional reacting two-phase flow problems. The intent of the original GIFS development effort was to provide the JANNAF community with a standard computational methodology to simulate multiple nozzle/plume flow-field phenomena and other three-dimensional effects. Recent development efforts have concentrated on improving the run time and robustness of the algorithm.

The GIFS computer program was originally released as an untested research version. Since that time, several corrections and enhancements have been made to the model. The Van Leer Flux Splitting option has been successfully implemented into the existing GIFS model and provides a more robust solution scheme. A Parabolized Navier-Stokes (PNS) version of the GIFS algorithm is currently under development and is intended to substantially improve the run-time requirements for flow fields dominated by supersonic flow regimes.

This paper reports the significant results of several applications of the GIFS model. Specifically, three separate 3D calculations of the Minuteman III first and third stage solid rocket motors with and without the base region were completed to assess the effect of the base in multiple nozzle/plume flow-field simulations. One additional 2D and two 3D calculations simulating the exhaust flow field of the Titan and the generic Ariane were completed to determine the three-dimensional effects and the impact of the single equivalent nozzle assumption in these flow environments. The results of these calculations indicate that the base region effect is significant for up to 14 nozzle exit diameters in axial plume length. In addition, three-dimensional effects are important in the plume near-field domain, and the equivalent single nozzle assumption is shown to be inaccurate in this region.

Introduction

In order to support testing and analysis requirements of the plume community, a need exists for a fluid dynamics model which solves the fully coupled two-phase Navier-Stokes equations in multiple dimensions. Evaluation of solid-propellant rocket motor performance, nozzle erosion, and solid-propellant rocket plume radiative transfer analyses requires a computer model which simulates complex three-dimensional, chemically reacting two-phase flow effects.[1] Although this type of full Navier-Stokes method provides an accurate qualitative description of the basic features of the propulsion-generated flow fields, quantitative simulations for predicting fundamental parameters such as base pressure, static pressure, temperature, and chemical composition in the flow-field domain have not been validated. In the past few years, significant progress has been made in the areas of numerical rocket flow simulations and computational resources to the point that Navier-Stokes solutions are viable analysis tools for quantitative assessments.

The flow fields generated by rocket propulsion systems are complex, with regions of strong inviscid/viscous interactions, free-stream shear layers, wall boundary layers (external and internal), shocks, separation regions, and, at downstream locations plumes/plume interactions.[2] Modeling these phenomena is a challenging task and is pushing the state of the art for CFD models. To account

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for all phenomena affecting plume flow properties and the resulting radiative transfer implications, computationally efficient multidimensional computer models are required. The numerics included in the model should be appropriate and should be validated over the operating conditions of interest. The ultimate objective for the "ideal" mature CFD tool is to be user-oriented and provide appropriate documentation and diagnostics to guide the novice user through a successful application. A careful systematic validation of the model should also be reported.[3] The GIFS model does not represent mature technology according to this definition. It is currently a research-oriented, state-of-the-art (SOA) computer program. Experience with GIFS indicates that it contains the technology required to address complex physics; however, efficiency, user friendliness, and robustness remain outstanding issues. We have made some strides toward this goal. GIFS has been modified to improve the code efficiency and user friendliness, and has been validated by comparison of the GIFS simulation results with a variety of experimental data ranging from subsonic through supersonic phenomena.[3]

The GIFS numerical algorithm provides a solution of the two- and three-dimensional Reynolds-averaged Navier-Stokes (NS) equations using the MacCormack implicit finite-volume algorithm with Gauss-Seidel line relaxation.[2] Several 2-D and 3-D plume flow-field calculations have been completed for the plume near-field region using the original GIFS model.[2] The GIFS model includes a frozen and a generalized finite-rate kinetic chemistry model, a Lagrangian particle model for treating solid or liquid particulates, and a two-equation turbulence model, as well as a laminar model. These complex phenomena are required to accurately simulate the physics expected to contribute to the subsequent plume signature. The original objective of the GIFS development was to provide a flowfield model to be used in conjunction with radiative transfer models to predict plume infrared emission characteristics resulting from three-dimensional, multiple nozzle propulsion configurations. The motivation for this study is to demonstrate the significance of three-dimensional effects as applied to multiple nozzle rocket missile plumes, to determine how these phenomena may be better simplified in order to promote improvements to engineering approaches, and to explore methods to reduce the overall CPU resource requirements for simulating three-dimensional solutions.

Code Enhancement

The results obtained from the GIFS code are based on the work reported in a previous published paper, "CFD Validation and Evaluation for Reacting Flows."[3] More than forty separate applications of the GIFS model indicate that the code can be a viable model for analyzing multiple plume and rocket base flows. However, due to the original code's excessive execution times, instabilities for highly underexpanded nozzle conditions, and user unfriendliness, it was extremely difficult to use for all but the motivated CFD expert. The original GIFS code has been modified to improve the code usability. The Van Leer Split Flux[4] has been incorporated into the GIFS code to improve the robustness of the model. Some recent results using this option are reported in this work. A 3-Dimensional Parabolized Navier-Stokes (3DPNS) option is currently being implemented into the GIFS algorithm. Many propulsion problems in two and three dimensions can be solved by employing a space-marching PNS technique. The flow regimes where a PNS solution is suitable include supersonic nozzle conditions and plume expansion regions. The use of the PNS algorithm offers significant savings in computational time, as well as reduced memory requirements and solution stability. Stability problems occurring in solutions involving high-altitude plume expansions and other flow regimes are shown to be improved by utilizing the Van Leer Split Flux option.

Code Validation

The modified 2D and 3D version of the GIFS code has been extensively tested for a variety of problems. In the earlier paper,[3] the GIFS code was compared with an established database for CFD code validation and evaluation. As reported in Ref. 3, GIFS was compared to experimental data taken from seven selected data sets. The validation database conditions includes: (1) supersonic flow over a rearward-facing step; (2) supersonic two-dimensional nozzle flow; (3) low subsonic reacting nozzle

flow; (4) combustion in two-dimensional supersonic flow with tangential hydrogen injection; (5) shear layer combustion in a supersonic concentric hydrogen/air flow; (6) hypersonic flow over a biconic model with perpendicular nitrogen injection; and (7) staged sonic normal injection of air behind a rearward-facing step into a Mach 2 airstream. In addition, GIFS was applied to calculate the rocket nozzle and plume flow field for an AEDC liquid-propellant rocket engine plume test case.

These results reported in the validation study indicate that the GIFS code can be a viable model for analyzing multi-plume and rocket base flows. However, due to excessive execution times and instabilities for the highly underexpanded nozzle cases and the level of CFD expertise required for application, the use of the code in its original form is not feasible for routine engineering purposes.

Solid-Propellant Rocket Plume

Minuteman Test Cases

The Minuteman first- and third-stage solid-propellant rocket motors (SRMs) are propelled by four nozzles located in a symmetric pattern about the centerline of the rocket base region. The geometries of the first and third stages are different. The nozzles for the first stage are contained within the motor body, whereas the nozzles for the third stage are exposed. To limit the number of grid points and CPU time, the configuration was modeled as a 45-deg wedge with two symmetry planes. This assumption is appropriate for zero angle of attack without any gimbaling of the nozzles.

The Minuteman calculations were executed for the first and third stages including finite-rate chemical kinetics and the κ-ε turbulence model. After a nearly converged gas-only flow-field solution was obtained, the solid aluminum oxide particles were introduced. The Al_2O_3 weight fraction for this motor is approximately 30 percent, a significant amount. As expected, the temperature of the plume increased substantially due to the energy carried by the particles. In these calculations, the GIFS starting conditions were initialized at the nozzle throat plane. The solid rocket chamber and nozzle throat conditions were calculated with a TDK transonic model which determined the GIFS startline condition.[5] The solid-propellant rocket motor chamber, nozzle throat, and external airflow conditions for the Minuteman III first and third stages are given in Tables 1 and 2. The finite-rate chemistry model assumed 13 species and 18 reactions for a carbon, hydrogen, oxygen, nitrogen (CHON) system. For the particle model, the solid aluminum oxide (Al_2O_3) density was given to be 3,873 kg/m^3, heat capacity 1300 J/(kg-K) and the particle radii ranged from 5 to 10 microns. Due to the large nozzle exit to ambient pressure ratio, the solution at the higher altitude condition of the third stage was unstable and very difficult to obtain. Figures 1 and 2 display planar contours at x/Rj = 6, (Rj = nozzle exit radius) of Mach number, and static temperature, respectively. Figure 3 displays particle trajectories for stage 1. Static temperature and Mach number contours for the third stage are shown in Figs. 4 and 5, at x/Rj = 3 and 6, respectively. The major features of this flow environment include:

- Expansion of the exhaust flow from Mach 1 at the throat of the nozzle to supersonic in the thrust chamber expansion region, followed by expansion/recompression of the exhaust plume,

Table 1. Minuteman First Stage, Properties of Chamber/Throat and External Flow

Chamber Temperature	6240 R
Chamber Pressure	740 psia
Throat Temperature	5780 R
Throat Pressure	424 psia
Altitude	20,000 ft
Free-stream Temperature	447.4 R
Free-stream Pressure	6.76 psia
Free-stream Mach	2.0

Table 2. Minuteman Third Stage, Properties of Chamber/Throat and External Condition

Chamber Temperature	6498 R
Chamber Pressure	265.0psia
Throat Temperature	5778. R
Throat Pressure	86.1 psia
Altitude	129,844 ft
Free-stream Temperature	449.7 R
Free-stream Pressure	0.0427psia
Free-stream Mach	3.5

- Interaction impingement of the four plumes near the axis of rotation, resulting in high temperatures and recirculation of the exhaust into the base region,

- The high temperatures throughout the entire plume near field are caused by the energy of the solid particles. The temperatures are slightly lower near the walls of the nozzle because the particles lag the expansion of the gas and do not completely fill this region.

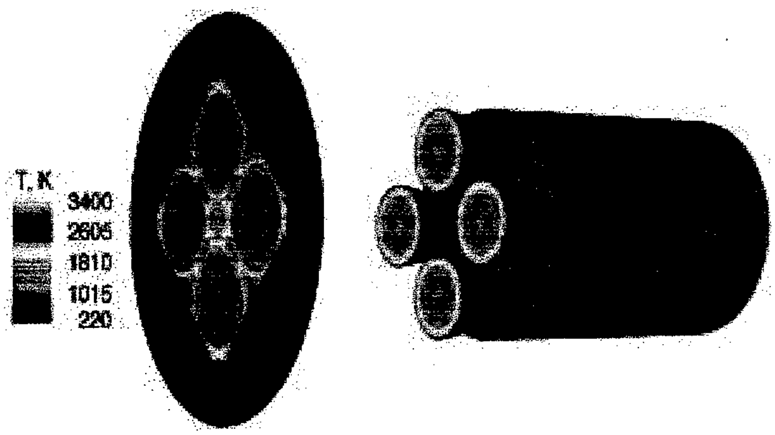

Fig. 1. Minuteman III 1st stage, temperature contours.

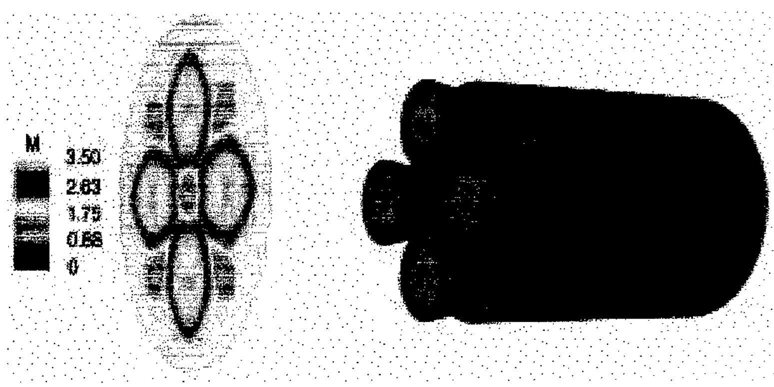

Fig. 2. Minuteman III 1st stage, Mach number contours.

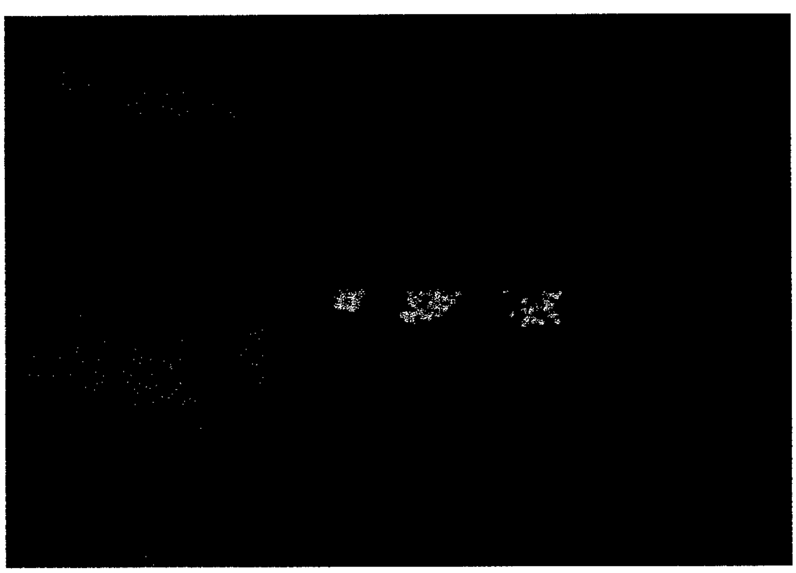

Fig. 3. Minuteman III 1st stage, particle trajectories.

Minuteman III Third Stage (Without Base)

The Minuteman III third stage calculation described above included the missile base region in the calculation domain. To determine the effect of the base in multiple nozzle/plume flow-field simulations, this calculation was repeated without the base. Mach number and temperature contours for the third stage at X/Rj = 4 and 8 (without the base) are shown in Figs. 6 and 7, respectively. Comparisons of the two solutions, with and without the base region, indicate that the effect of the base is significant up to 14 nozzle exit diameters in axial plume length. The comparison of these two calculations indicates that accurate prediction of the flow-field properties in the near-field region requires that the base region be included in the solution. The results indicate that the simplification included in some engineering approaches which ignores the base region effects or globally approximates the effects of the base will not properly simulate the plume near-field. For pro-

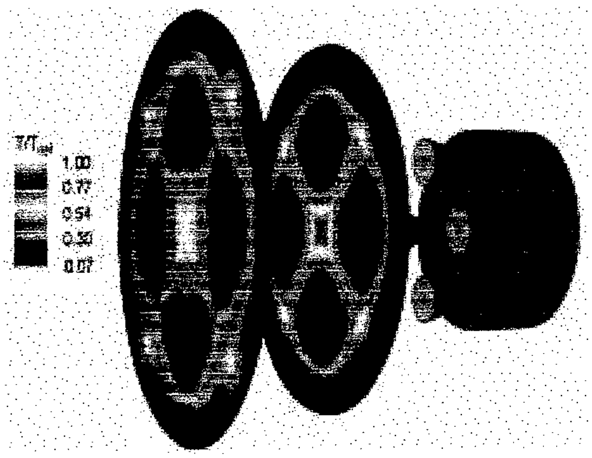

Fig. 4. Minuteman III, 3rd Stage (M57), temperature contours.

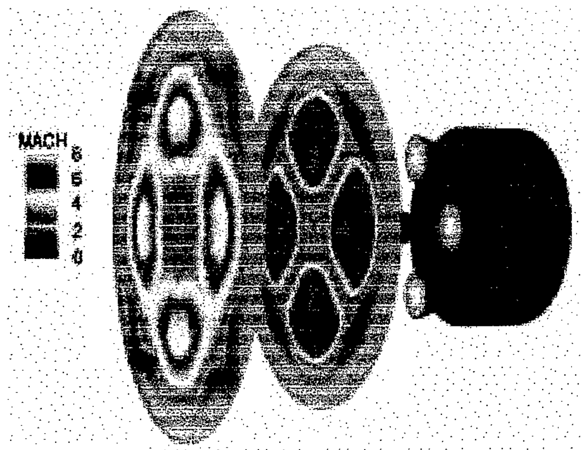

Fig. 5. Minuteman III, 3rd Stage (M57), Mach number contours.

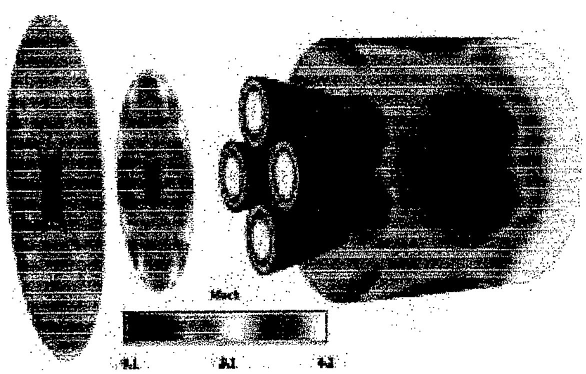

Fig. 6. Minuteman III without base, Mach number contours.

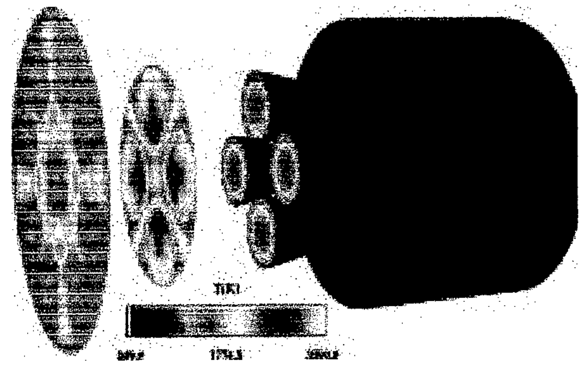

Fig. 7. Minuteman III without base, static temperature contours.

pulsion systems having a base region, a more detailed Navier-Stokes flow solver is required.

Titan Test Case

The Titan III liquid propulsion system is propelled by two engines located on either side of a plane of symmetry bisecting the rocket body. This geometry was modeled as a 90-deg wedge with two symmetry planes. This assumption is appropriate for zero angle of attack without any gimbaling of the nozzles. The flow-field domain was divided into five zones as shown in Fig. 8. The external airflow conditions and the liquid rocket nozzle throat boundary condition for the Titan test case are given in Table 3. The Titan 3D calculation included finite-rate chemistry (13 species and 18 reactions, CHON system) and the κ–ε turbulence model. This calculation domain included the complete missile body and the propulsion system. Figures 9 and 10

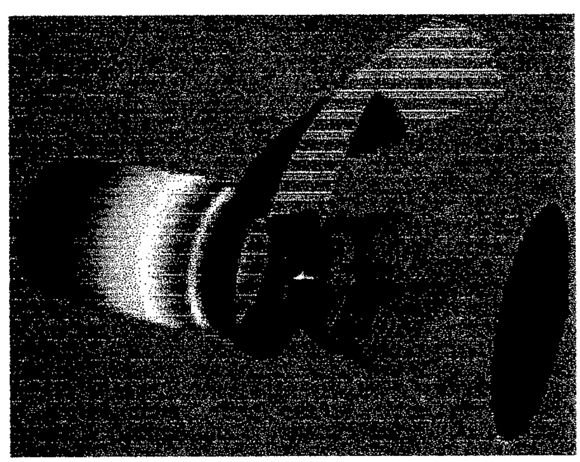

Fig. 8. Titan grid and nozzle flow field configuration.

display contours of static temperature and Mach number in the flow field. The dominant features of this flow field can be summarized as follows: expansion of the exhaust flow from Mach 1 at the throat to supersonic flow downstream; interaction of the two plumes near the plane of symmetry between the nozzles, including heating caused by this interaction. Because of the close proximity of the nozzles, this initial interaction occurs at a short distance downstream of the exit plane and results in a very strong interaction effect. The original version of the GIFS code was very unstable for this test case and did not converge; however, the enhanced version of the code, which includes Van Leer Split Flux, was stable and executed without any problem.

In the second part of the Titan test case study, a simplified 2D axisymmetric geometry was used

Table 3. Titan External and Chamber/Throat Conditions

Property	Value
Chamber Temperature	5900 R
Chamber Pressure	778 psia
Throat Temperature	5500 R
Throat Pressure	450 psia
External	
Altitude	120,000 ft
Pressure	0.064 psia
Temperature	434 R
Mach Number	4.0

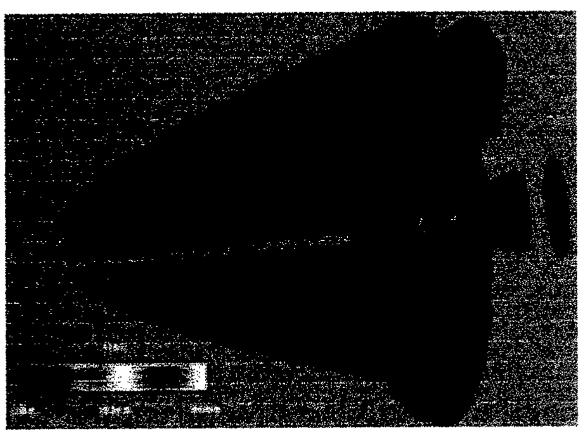

Fig. 9. Titan III with finite rate chemistry, temperature contours.

to study and compare the 2D and 3D solutions. The Titan geometry is not axisymmetric and can only be approximated with a 3D grid. A comparison of the two-dimensional axisymmetric solution with the three-dimensional twin-nozzle solution was accomplished to determine the impact of the single equivalent nozzle assumption. Figure 11 provides a comparison of the axisymmetric and the 3-D solutions. There are significant differences between the two solutions, including the plume size asymmetric flow distributions and the location of the shock reflection points. This illustrates that a

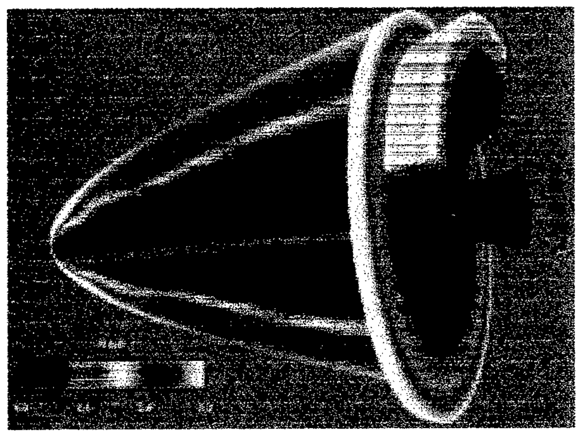

Fig. 10. Titan III with finite rate chemistry, Mach No. contours.

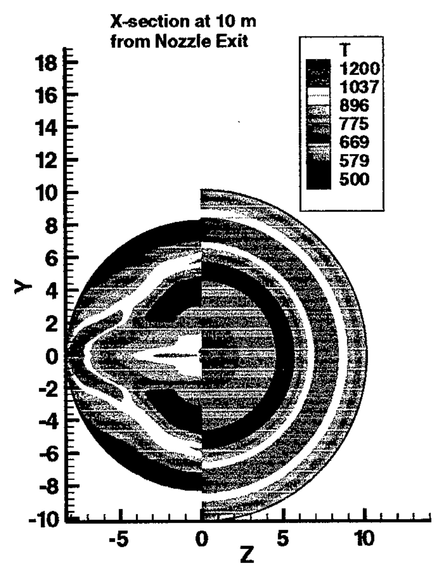

Fig. 11. Static temperature cross section comparisons, 3-D plume vs. single equivalet nozzle.

single equivalent nozzle assumption provides valuable insight concerning overall gross qualitative assessments; however, for detailed studies requiring accurate resolution of the spatial character of multinozzle plume flows, a three-dimensional calculation is required.

Generic Ariane Test Case

The Ariane 4 liquid propulsion system is propelled by four 11:1 expansion ratio nozzles located in a symmetric pattern about the rocket body centerline. The length of the nozzles (throat to exit) is 5.25 ft, and the nozzles are gimbaled outward by an angle of 4.2 deg. A conical fairing approximately 14.7 ft long extends from the rocket body into the base region to divert external airflow away from the nozzles. This generic configuration was modeled as a 45-deg wedge with two symmetry planes. This assumption is appropriate for zero angle of attack with symmetric gimbaling of the nozzles. This generic Ariane calculation included kinetic finite-rate chemistry (13 species and 18 reactions for a CHON system) and the κ–ε turbulence model. The subsonic liquid-propellant rocket chamber and transonic nozzle throat conditions were modeled separately (as before) assuming chemical equilibrium conditions. The chamber and throat conditions are summarized in Table 4. The external flow conditions are also specified in Table 4. This calculational domain included the complete missile body and the propulsion system. Using this approach, the effect of the missile body aerodynamics on the free-stream flow conditions are simulated. The original version of GIFS was very unstable when the missile body was included in the computational domain. Stability was not an issue with the enhanced version with the Van Leer Flux Splitting algorithm.

Figure 12 display contours of static temperature in a symmetry plane cutting through one of the four nozzles and a cross section view very near the nozzle exit location. The major flow features apparent in these plots are expansion of the plumes from Mach 1 at the nozzle throat to over Mach 7 in the downstream plume expansion. The interaction of the four plumes near the plane of the symmetry between the nozzles is indicated by the high temperature region. Because of the large spacing between the nozzles, the interaction in this case is relatively weak, but still results in temperatures close to the stagnation temperature over a small area. This test case was initially executed with the original version of the code which used MacCormack Flux Splitting. After the first few hundred iterations, this solution became unstable and terminated. The same case was repeated with the Van Leer Flux Splitting and converged in approximately 2000 iterations.

Table 4. Generic Ariane External and Throat Conditions

Property	Value
Chamber Temperature	5450 R
Chamber Pressure	836 PSIA
Throat Temperature	5000 R
Throat Pressure	478 PSIA
External	
Altitude	120,000 Ft
Pressure	0.064 PSIA
Temperature	434 R
Mach Number	4.0

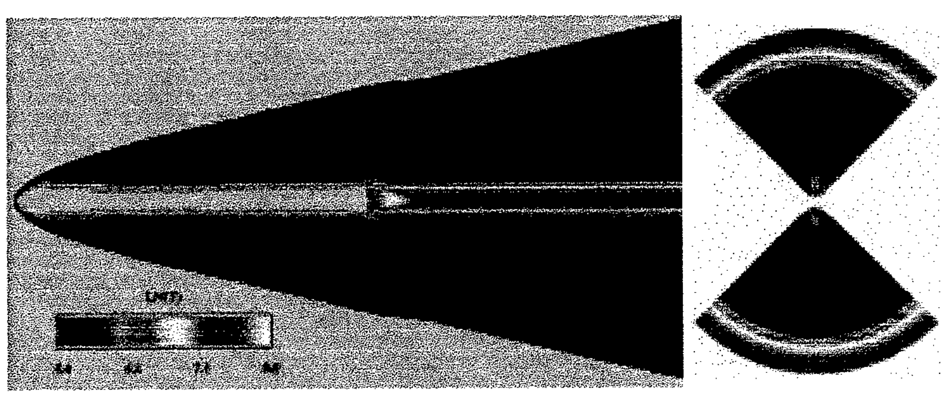

Fig. 12. Generic Ariane static temperature contours with finite rate chemistry (liquid propellant) alt. 120 kft.

Conclusions and Recommendations

Application of a reliable CFD methodology in the assessment of rocket/plume flow-field phenomena and radiative transfer can support experiment planning and tremendously enhance the analysis and understanding of experimental measurements. The primary objectives of the work reported here involved two efforts, enhancement of the GIFS code from an operational, engineering tool application and application of the GIFS code to simulate multi-nozzle/plume and rocket base flow and geometry-related phenomena.

The original GIFS code has been modified to improve the code execution reliability and user interface. A Van Leer Flux Splitting option has been incorporated into the GIFS code. The Van Leer Flux modification of the GIFS code was applied for several 3D plume flow field calculations. GIFS was applied to model the Minuteman III first- and third-stages solid-propellant rocket motors with and without the base region included in the calculation. A comparison of these calculations indicates that the base region effect is significant to axial locations extending to approximately14 nozzle exit diameters. The GIFS code was applied to simulate the 3D Titan plumes and a simplified 2D geometry of the Titan. A comparison of the 2D and 3D calculations indicates that the three-dimensional effects are important in the near-field plume, and the equivalent single nozzle simplification is inaccurate, specifically in the near-field domain.

The final test case evaluated by the GIFS code was a generic Ariane rocket plume simulation. The purpose of this calculation was to demonstrate the capability to generate a solution, including the missile body portion and the external flow around the body combined with the propulsion system flow field. The GIFS code was able to handle all regimes of the flow environmental and produced reasonable results.

The current government standard rocket nozzle/exhaust plume computer models assume single axisymmetric nozzles and approximate the base flow effects in a global sense. Propulsion systems which do not meet these geometry requirements are often approximated using an "equivalent-type" pseudo axisymmetric geometry. The level of approximation affects the accuracy of the results. For many BMDO and AEDC testing requirements, the phenomena of the base region and the 3D effects are important and must be resolved in the model. The results reported here indicate that the GIFS code can be a viable model for analyzing multi-plume and rocket base flow phenomena.

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